

# Baryon-baryon interactions in free space and baryonic medium

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## Abstract

We study the interactions of the octet baryons in a relativistic meson exchange approach connecting free-space and in-medium interactions with those in finite (hyper)nuclei. A short sketch of the model including the relativistic T- and G-matrix and the mapping of the G-matrix onto density dependent vertex functionals in the density dependent relativistic hadron field theory (DDRH) is given. From new spectroscopic data on medium mass hypernuclei we extract the single particle spectrum including spin-orbit splitting. An extraction of the  $\Lambda\omega$  vector- and tensor vertex as well as the  $\Lambda\sigma$ -vertex shows a strong breaking of SU(3) symmetry.

## 1 Introduction

The presented approach aims at a microscopic link between interactions for free baryon-baryon scattering, their in-medium interaction in infinite matter and in finite nuclei. Such a comprehensive description is essential for extrapolations to not yet experimentally observed or even never observable regions of the (hyper)nuclear chart, infinite hypermatter in neutron stars and baryon-baryon interactions in heavy ion collisions. In the nuclear sector there is abundant information available, i.e., the coupling constant can be fixed from free NN scattering and then propagated to finite nuclei where calculations of their properties and comparison to experimental data yield an important check of consistency. In the hyperon sector the model can be used then to extract from single particle spectra of hypernuclei free hyperon coupling constants which are inaccessible otherwise.

## 2 The density dependent relativistic hadron field theory

Our approach is based on the covariant meson exchange framework. To generate the effective microscopic interaction in finite nuclei an approach using

T-matrix theory with a three dimensionally reduced two-nucleon propagator is applied. In this way the same mesons with the same bare couplings are used throughout the model. The in-medium interaction is calculated in Dirac-Brueckner theory, i.e., a T-matrix calculation in infinite matter where the intermediate two-baryon propagators are Pauli-blocked and dressed by Hartree-Fock self-energies. Since a G-matrix calculation for finite nuclei is technically not feasible DDRH theory is used to apply the G-matrix interactions in calculations of finite nuclei.

DDRH theory [1] is a Walecka type model designed for relativistic mean-field (RMF) calculations of finite nuclei using G-matrix interactions. Contrary to the conventional RMF models density dependent vertex functionals  $\Gamma(\hat{\rho})$  are used instead of constant couplings and meson self-interactions to account for finite density effects.  $\hat{\rho}$  is a bilinear of the baryonic field operators. Using the self-energies, in-medium effects of the G-matrix interaction are mapped onto the vertex functionals [1, 2]. Deriving the Dirac equation from the DDRH Lagrangian yields additional *rearrangement self-energies*, coming from the variation of the vertex functionals with respect to the baryonic field operators and describing static polarizations of the nuclear medium [1]. They do not affect the bulk properties of a nucleus but modify the single particle structure only. This treatment of the density dependence leads to a covariant field theoretically and thermodynamically consistent theory (see [1] for the proofs). DDRH theory was applied successfully to magic and exotic nuclei in RMF approximation [1, 2].

### 3 Hypernuclear structure

Hypernuclear spectroscopy has made important progress in accuracy in the recent years, allowing now to extract information about the interaction systematics between hyperons and nucleons within a microscopic model. With this understanding of the interaction and upcoming even more precise  $\gamma$ -spectroscopy experiments on hypernuclei at KEK, JLab, GSI and MAMI-C it will even be possible to study more subtle interaction effects beyond the mean-field which are not accessible in such a clean way using nucleon spectroscopy and conventional nuclear structure.

#### 3.1 DDRH for hypernuclei

DDRH theory has been extended from the use in pure isospin nuclei to hypernuclei involving the octet baryons [3] and to hyperon star matter [4]. Lacking

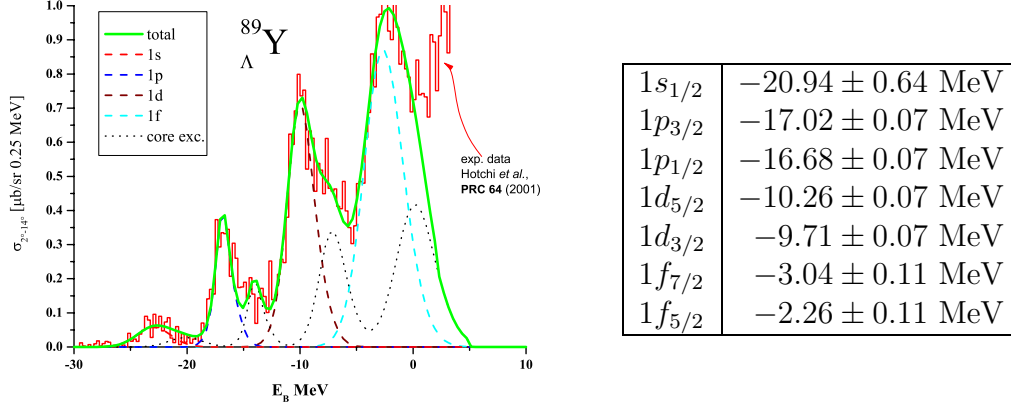


Figure 1: The figure shows the refined fit to extract the single particle spectrum from the experimental data, taking also into account  $jj$  interactions. In the table the extracted single particle spectrum of  $^{89}_{\Lambda}Y$  is shown.

a G-matrix calculation for the complete baryon octet – work is in progress on that – an approximate treatment of the hyperon-meson vertices was obtained from a diagrammatic analysis of the Dirac-Brueckner equations. It was shown [3] that the functional shape of the vertices should be approximately the same as that of the nuclear ones, depending on the density of the respective hyperon iso-multiplet instead of the nuclear density. The strength has to be rescaled by a function  $R_{Y\alpha}$  which turns out to be approximately constant and can in first order be related to the free coupling constants as  $R_{Y\alpha} = \frac{g_{Y\alpha}}{g_{N\alpha}}$ .

Single  $\Lambda$  hypernuclei are the only well known hypernuclear systems. The  $\Lambda$  being an isoscalar and electrically neutral baryon just couples to the  $\sigma$  and the  $\omega$  meson simplifies its theoretical description tremendously. The two corresponding scaling factors relate directly to the free couplings  $g_{\Lambda\sigma}$  and  $g_{\Lambda\omega}$  by the approximate relations given above. Using spectral information of hypernuclear spectroscopy including resolved spin-orbit doublets these two constants can be extracted unambiguously from DDRH RMF calculations for the respective hypernucleus – or incompatibilities of the calculated and measured spectral structures will give definite hints to deformations and dynamics beyond mean field.

### 3.2 Evaluation of experimental data

Recent experimental data measured at KEK on  ${}_{\Lambda}^{89}\text{Y}$  and  ${}_{\Lambda}^{51}\text{V}$  [5] show a significant broadening of the single particle peaks as compared to the experimental resolution. The simple analysis with a two uncorrelated gaussian fit of each single particle peak - motivated by a spin-orbit (s.o.) splitting assumption - which was performed in [5] lead to a single particle spectrum which could not be reproduced by DDRH RMF calculations. Taking into account also the high ground state spin of the  ${}^{88}\text{Y}$  and  ${}^{50}\text{V}$  cores with  $I^{\pi} = 4^{+}, 6^{+}$ , respectively, we performed a refit of the data. The broad single particle peaks were modeled by two gaussians of which the individual strength was constrained by the relative multiplicities of their s.o. states. The width of each gaussian and the relative distance of their means were fixed by assuming the spin dependent part of the single particle energies to be  $E_s = E_{ls} \langle l \cdot s \rangle + E_{jj} \langle I \cdot j \rangle$  ( $I$  being the core spin and  $j$  the total angular momentum of the  $\Lambda$  state). The s.o. and  $jj$  matrix elements are the same for the whole fitting procedure. In contrast to the fit with uncorrelated gaussians our fit gets significantly more stable. A strong reduction of the s.o. strength compared to the simpler fit is observed being consistent with high precision measurements of the s.o. splitting in  ${}^{13}\text{C}$  [6]. The s.o. and  $jj$  matrix elements are obtained as  $E_{ls} = 223 \pm 153 \text{ keV}$  and  $E_{jj} = 61 \pm 3 \text{ keV}$ .

### 3.3 Hypernuclear structure calculation with DDRH

The fairly small s.o. splitting brings into the game the formerly already discussed  $\Lambda\omega$  tensor interaction (see, e.g., [7]). This tensor interaction introduces terms proportional to  $\bar{\psi}\sigma^{\mu\nu}\psi\partial_{\mu}\omega_{\nu}$  in the interaction Lagrangian being of the same Dirac structure as the s.o. interaction in the Dirac equation. According to spin-flavor SU(6) the tensor vertex "f" is minus that of the vector interaction "g", leading to an almost vanishing s.o. splitting.

Including the tensor interaction we performed a least squares fit of calculated DDRH RMF  $\Lambda$  single particle energies to the experimental ones with respect to the variables  $R_{\sigma}$ ,  $R_{\omega}$  and  $f/g$  (which should be 2/3, 2/3 and  $-1$ , respectively, according to SU(3)). A very strong linear correlation between  $R_{\sigma}$  and  $R_{\omega}$  is found, induced by the spectral gross structure (known already from earlier hypernuclear RMF calculations not considering s.o. splitting [3]). The favored region with  $\chi^2 < 1$  is shown in fig. 2. It is centered around  $R_{\sigma}(=R_{\omega}) = 0.25$  and  $f/g = 0$ . This indicates a substantial violation of SU(3) symmetry. Effects which are still under investigation and might lead to minor changes are for example the influence of deformations of the nuclear core. Calculations for

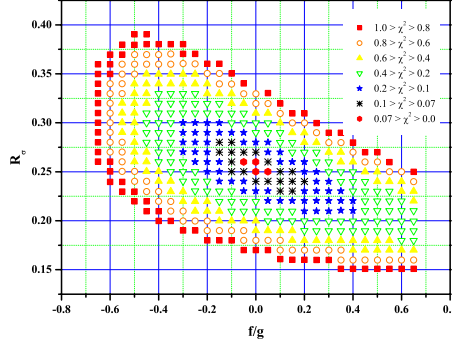


Figure 2:  $\chi^2$  plane of fitting the  $\Lambda$  meson coupling constants to match the experimental single particle spectrum.

the world data set on hypernuclei with an even-even core is shown in fig. 3. The calculation with our new parametrization (dots linked by the solid line) shows clear improvements especially in the low mass region compared to our previous parameters.

Concerning model building the strong violation of  $SU(3)$  symmetry is both-er since  $SU(3)$  relations used in the derivation of, e.g., hyperon-hyperon interactions could no longer be applied. From the nuclear structure point of view the very weak  $\Lambda$  couplings are in contrast very encouraging. Since the strange sector seems to almost decouple from the isospin sector it might be possible in future high accuracy spectroscopic experiments to measure nuclear bulk properties like mass radii and deformations through  $\Lambda$  hypernuclear spectroscopy.

## 4 Conclusions

The accuracy of the discussed experimental data is already at the limits of what can be expected from meson spectroscopy of hypernuclei. Still, looking at the large uncertainties in the determination of coupling constants from these data, see fig. 2, more precise measurements are needed. These will be provided by the beginning new era of  $\gamma$  spectroscopy experiments on hypernuclei. On the theory side it will be essential to replace the approximate treatment of the in-medium  $\Lambda$  interactions by a fully microscopic one. Work on such a Dirac-Brueckner G-matrix calculation is in progress.

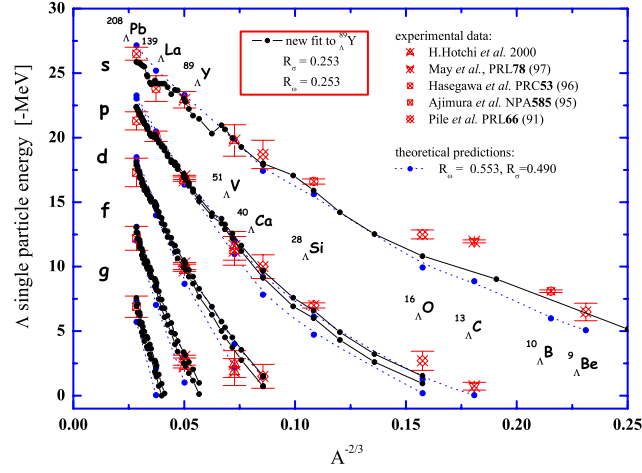


Figure 3: DDRH  $\Lambda$  single particle spectra compared to the world data.

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